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RESEARCH MEMORANDUM

AN EXPERIMENTAL INVESTIGATION OF THE COMBUSTION
PROPERTIES OF A HYDROCARBON FUEL AND SEVERAL
MAGNESIUM AND BORON SLURRIES

By Albert M. Lord

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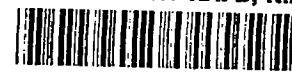
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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUMAN EXPERIMENTAL INVESTIGATION OF THE COMBUSTION PROPERTIES OF A
HYDROCARBON FUEL AND SEVERAL MAGNESIUM AND BORON SLURRIES

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SUMMARY

An investigation was conducted to explore the characteristics of metal - hydrocarbon combustion, to determine the effect of fuel-air ratio on the combustion efficiency, and to determine how the metal and hydrocarbon separately contribute to the over-all combustion of several slurries. MIL-F-5624 grade JP-3 fuel and slurries of magnesium and boron in JP-3 fuel were investigated.

The combustion efficiency (ratio of energy released to energy available by complete combustion) of magnesium powders in slurries was unaffected by oxygen depletion as fuel-air ratio was increased above stoichiometric to an equivalence ratio of 1.6, whereas the combustion efficiency of the hydrocarbon declined rapidly. This indicated that the magnesium burns first and the hydrocarbon reaction yields increasing amounts of incomplete combustion products. This effect did not appear in the boron slurries where the oxygen deficiency in the rich region was reflected in incomplete combustion of both the boron and hydrocarbon.

The relative changes in the combustion efficiencies of the metal and the hydrocarbon with equivalence ratio in effect changed the ratio of metal to slurry that was utilized in the combustion (effective metal fraction). For the range of the experimental data the effective metal fraction was higher at rich mixtures than at lean mixtures; the effective heating value per pound of air was correspondingly higher in the rich region.

The heat released by combustion per pound of air of all the fuels was increased over the values at equivalence ratio of 1.0 by increasing the fuel-air ratio above stoichiometric.

INTRODUCTION

The use of metal - hydrocarbon slurries as fuels in jet-engine propulsion systems has been the subject of analytical and experimental

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investigations at the NACA Lewis laboratory. As a result of these investigations, substantial improvements in air specific impulse have been realized in an experimental afterburner by the addition of magnesium powder to conventional hydrocarbon fuel (reference 1). It was also found that combustion stability was improved by the metal powder.

The higher air specific impulse of the metal - hydrocarbon slurry over the hydrocarbon alone is due partly to the higher heat of combustion per pound of air of the slurry when compared with the hydrocarbon at the same equivalence ratio. References 2 to 4 report the results of analytical investigations in which the equations of chemical equilibrium were solved for the composition and temperature of the combustion products of octene-1, and mixtures of aluminum, magnesium, and boron in octene-1 when burned in air. Values of theoretical air specific impulse at stoichiometric fuel-air ratio for octene and the slurries were computed and shown to be higher for each of the slurries than for the hydrocarbon.

In the present investigation the characteristics of metal - hydrocarbon combustion were explored to determine the effect of fuel-air ratio on combustion efficiency and to determine how the metal and hydrocarbon separately contribute to the over-all combustion. A slurry was atomized and burned in a 2-inch burner. A sampling probe collected gaseous and solid combustion products. The composition of the samples was determined by chemical analysis. The fuel-air ratio, combustion efficiency, effective metal fraction, and heat released by combustion were computed from the composition of the combustion products of the following fuels: MIL-F-5624 grade JP-3 and slurries of boron and magnesium in JP-3 fuel.

SYMBOLS

The following symbols are used in this report:

CO_2/CO	molecular weight ratio of CO_2 to CO when CO burns to CO_2
f	fuel-air weight ratio determined by flow rate measurement of air and fuel
f'	fuel-air weight ratio determined by sampling and analyzing combustion products
H/C	hydrogen-carbon weight ratio
$(\text{H/C})_{\text{eff}}$	effective hydrogen-carbon weight ratio
h_c	heat of combustion of carbon to carbon dioxide (Btu/lb carbon)
h_{CO}	heat of combustion of carbon to carbon monoxide (Btu/lb CO)

h_{CO_2}	heat of combustion of carbon to carbon dioxide (Btu/lb CO_2)
h_{HC}	heat of combustion of hydrocarbon (lower value) (18,700 Btu/lb hydrocarbon)
h_{H_2O}	heat of combustion of hydrogen to water (lower value) (Btu/lb H_2O)
h_M	heat of combustion of metal to metal oxide (Btu/lb metal) (Magnesium, 10,813 Btu/lb; boron, 23,281 Btu/lb)
Q	heat released by combustion (experimental) (Btu/lb air)
W_C	weight of solid carbon in combustion sample ¹
W_{CO}	weight of carbon monoxide in combustion sample ¹
W_{CO_2}	weight of carbon dioxide in combustion sample ¹
W'_{CO_2}	weight of carbon dioxide formed by catalytic combustion of hydrocarbon residues in combustion sample ¹
W_{HC}/W_a	hydrocarbon-air weight ratio
W_{HC}/W_f	hydrocarbon weight fraction of slurry fuel
W_{H_2O}	weight of water in combustion sample ¹
W'_{H_2O}	weight of water formed by catalytic combustion of hydro- carbon residues in combustion sample ¹
W_M	weight of uncombined metal in combustion sample ¹
W_M/W_a	metal-air weight ratio
W_M/W_f	metal weight fraction of slurry fuel
$(W_M/W_f)_{eff}$	effective metal weight fraction of slurry fuel
W_m/W_{mo_x}	molecular weight ratio of metal to its oxide
W_S	weight of solids combustion sample ¹
η_C	combustion efficiency of carbon

¹The combustion sample was the total of gas and solids drawn through the sampling probe.

η_H	combustion efficiency of hydrogen
η_{HC}	combustion efficiency of hydrocarbon
η_M	combustion efficiency of metal
ϕ	over-all equivalence ratio

APPARATUS AND PROCEDURE

The slurry burner and exhaust sampling apparatus are shown in figure 1. The burner consisted of a $1\frac{7}{8}$ -inch inside diameter tube 20 inches long. A tube liner with an outside diameter of $1\frac{5}{8}$ inches, a thickness of $1/16$ inch, and length of 2 inches and mounted at the inlet provided a small primary zone through which the atomized fuel was introduced. Secondary air was introduced as an annular stream along the burner wall. The secondary-air inlet was about 1 inch from the burner entrance.

The slurry was atomized and injected into the burner with a conventional paint spray gun of the type that pressurizes the fluid. The spray nozzle was sealed to the burner entrance. The flow rate of the fuel was set by a valve on the spray gun and was measured by weighing the spray gun before and after a timed test-run flow interval.

The flow rate of the air entering the burner was measured with a rotameter. The air flow was adjusted to give an inlet-air velocity of 22 feet per second.

The burner was ignited by opening the seal between the gun and the burner and holding an acetylene torch to the opening.

The sampling-probe assembly consisted of a $1/4$ -inch outside diameter copper tube encased in a water jacket. The outer wall of the jacket was covered with asbestos insulation. The $1/4$ -inch copper tube was connected to a solid sampling tube which was packed with glass wool to collect the metal oxide, unburned metal, and carbon particles. The assembly was mounted so it could be swung into the path of the flame, as indicated in figure 1. A rubber stopper sealed the opening of the probe. It was held in place by atmospheric pressure when the sampling apparatus was evacuated. As the probe moved toward the center of the burner exit, the stopper was brushed off by the edge of the burner, thus permitting the exhaust gases and solids to be drawn in.

A 30-gallon vacuum tank was evacuated by the vacuum pump to about 1 inch of mercury absolute. The valve between pump and tank was closed while a sample was taken. The pressure in the tank was measured with a mercury manometer.

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The exhaust-gas sample was collected in the gas sampling tube as follows: Both valves on the gas sampling tube were open when the sampling began, the downstream valve was closed after about 20 seconds of burner operation, and then the upstream valve was closed after the pressure in the sampling tube had risen to atmospheric.

A coil of copper tubing packed in powdered dry ice served to remove the moisture from the gases entering the vacuum tank. The total flow into the probe during the sampling period was computed from the pressure rise in the vacuum tank and gas composition data.

Description of fuels. - Tests were made with the following slurries and the hydrocarbon carrier alone:

- (1) 50 percent by weight fine magnesium in JP-3 fuel (spherical particles, 66 microns average diam. on weight basis)
- (2) 50 percent by weight superfine magnesium in JP-3 fuel (spherical particles, 24 microns average diam. on weight basis)
- (3) 50 percent by weight superfine magnesium in JP-3 fuel plus 0.8 percent gelling agent
- (4) 30 percent by weight crystalline boron in JP-3 fuel (particle size reported by manufacturer as less than 1 micron, manufactured by electrolytic process)
- (5) 30 percent by weight amorphous boron assumed 86 percent pure in JP-3 fuel (particle size, 21 micron average diam. on weight basis manufactured by magnesium reduction method)
- (6) MIL-F-5624 grade JP-3 fuel

The particle size distributions of the superfine magnesium, fine magnesium, and amorphous boron powders are given in figure 2.

The magnesium and crystalline boron powders contained a negligible fraction of impurities. The amorphous boron was reported by the supplier to contain approximately 14 percent inert material. The material was analyzed at the Lewis laboratory and a substantially lower metal content than was indicated by the supplier was found. The difference is apparently due to differences in analytical procedure and the methods used for accounting for other uncombined metals. The results presented in this investigation were based on the assumption that the supplier's report of 86 percent boron purity and 14 percent inert material was correct.

The JP-3 fuel conformed to specification MIL-F-5624.

The additive in slurry number (3) consisted of 75 percent aluminum octoate, 22.5 percent turpentine, and 2.5 percent magnesium stearate. This additive served to thicken and stabilize the slurry (reduced the tendency for the powder to settle out of the liquid).

A more complete description and discussion of the magnesium and amorphous boron powders, the JP-3 fuel, and the additive are given in reference 5.

The quantity of the combustion sample referred to in subsequent definitions includes all the combustion products drawn through the sampling probe. It is computed from the composition of the gases in the sample tube and the pressure rise in the vacuum tank, and the weight of the solids sample.

By analysis of the solids and gas samples the weights of the following constituents of the combustion sample were determined: N_2 , CO_2 , CO , H_2O , total solids, carbon, uncombined metal, and CO_2 and H_2O formed by catalytic combustion of unburned hydrocarbons in the sample.

The analysis of the gaseous products was determined with an Orsat apparatus equipped with a catalytic heater for the combustion of hydrocarbon residues. The nitrides in the solids samples were found to be less than 0.1 percent and were neglected. No carbonates were found in the solids.

The amount of uncombined magnesium in the solids samples of magnesium-slurry combustion products was determined by introducing an acid solution into the filter tube and measuring the volume of the hydrogen that was evolved. The solids sampling tube was weighed before the sampling, washed with distilled water after the acid treatment, dried, and weighed again. The gain in weight was taken as solid carbon.

The amount of uncombined boron in the solids samples of boron-slurry combustion products was determined by weighing the solids sampling tube before the sampling, running hot water through it after the sampling until all the boron oxide was leached out, drying the tube in a furnace, and then weighing it again. The gain in weight was taken as uncombined boron. From visual observation it was determined that no solid carbon was present in the boron-slurry combustion products.

Computations. - The combustion efficiencies reported herein are not based upon chemical equilibrium of the products of combustion inasmuch as data are not available for the various species involved. Instead, 100-percent combustion efficiency assumes the components (if present) oxidize as follows:

H₂ to H₂O

C to CO₂

Mg to MgO

B to B₂O₃

The combustion efficiency of the metal is defined as

$$\eta_M = \frac{\left[W_S - (W_{M'} + W_C) \right] \frac{W_m}{W_{mO_x}}}{\left[W_S - (W_{M'} + W_C) \right] \frac{W_m}{W_{mO_x}} + W_{M'}}$$

Appropriate corrections were made where the metal fuel contained inert impurities.

The combustion efficiency of the hydrocarbon is defined as

$$\eta_{HC} = \frac{W_{CO_2} \times h_{CO_2} + W_{CO} \times h_{CO} + W_{H_2O} \times h_{H_2O}}{\left(W_{CO_2} + W_{CO} \frac{CO_2}{CO} + W'_{CO_2} \right) h_{CO_2} + \left(W_{H_2O} + W'_{H_2O} \right) h_{H_2O} + W_C h_C}$$

The combustion efficiency of the hydrogen in the hydrocarbon is defined as

$$\eta_H = \frac{W_{H_2O} \times h_{H_2O}}{\left(W_{H_2O} + W'_{H_2O} \right) h_{H_2O}}$$

The combustion efficiency of the carbon in the hydrocarbon is defined as

$$\eta_C = \frac{W_{CO_2} \times h_{CO_2} + W_{CO} \times h_{CO}}{\left(W_{CO_2} + W_{CO} \frac{CO_2}{CO} + W'_{CO_2} \right) h_{CO_2} + W_C h_C}$$

Combustion efficiencies so defined are in substantial agreement with the conventional combustion efficiency at and below an equivalence ratio of unity. At equivalence ratios higher than one, the combustion efficiencies do not account for deficiency of oxygen as they are based only on the utilization of fuel.

The heat released by combustion per pound of air at various fuel-air ratios was found by

$$Q = f' (W_M/W_F \times \eta_M \times h_M + W_{HC}/W_F \times \eta_{HC} \times h_{HC})$$

RESULTS

Evaluation of sampling method. - A comparison of the fuel-air ratio determined by inlet air and fuel flow f and the fuel-air ratio determined by exhaust products analysis f' is shown in figures 3(a) to 3(f). The dashed line in each figure represents the ideal. It is seen that the f' points average about 25 percent below the corresponding f . The slurry atomizing nozzle used for these tests experienced partial clogging as the run progressed. Only the slurry flow was reduced, the air flow remained constant; thus the mixture tended to become leaner with time. The sample was always taken during the latter part of the test run and f was an average value for the entire run; hence, the nonuniformity of flow would be expected to introduce a difference in the values of f and f' in the direction indicated in figure 3.

From figure 3(f) it is seen that with JP-3 fuel alone the fuel-air ratios determined by analysis are also lower than those determined by flow rate measurement, but the difference is smaller than with the slurries. All the samples were taken at the center of the burner exit. It is probable that a radial deviation of fuel-air ratios existed in the burner.

The metal-hydrocarbon ratio as found by combustion products analysis is shown in the plots of metal-air ratio W_M/W_a against hydrocarbon-air ratio W_{HC}/W_a in figures 4(a) to 4(e). The dashed line in each figure represents the metal - hydrocarbon weight ratio used in making the slurry.

With few exceptions the metal - hydrocarbon ratio as found by analysis was lower than that used to make the slurry. A possible explanation for the discrepancy is that the quantity of solid products in the exhaust stream was reduced by the amount of oxide which adhered to the burner walls and then flaked off in agglomerations that were too large to enter the sampling probe. Oxide particles as large as 1/2 inch were observed in the burner exhaust stream.

Combustion efficiency. - The effect of fuel-air ratio f' and equivalence ratio ϕ on the combustion efficiency of the metal η_M and the hydrocarbon η_{HC} in each of the slurries is shown in figures 5(a) to 5(e). In figure 5(f) the combustion efficiency of JP-3 fuel alone is shown along with the separate combustion efficiencies of the hydrogen and carbon.

In order to show how the combustion efficiency values are modified by taking into account the effect of oxygen deficiency, a curve of combustion efficiency of the hydrocarbon in the rich region computed by the definition $\eta = \frac{Q/f'}{h_{HC}/\phi}$ when $\phi > 1$ is included in figure 5(f). The denominator h_{HC}/ϕ is the heat released by combustion when

- (1) All the oxygen is consumed
- (2) The composition of the combustion products (excluding nitrogen and unburned fuel) is the same as that resulting from complete combustion of a stoichiometric mixture.

The following effects are noted:

(1) Combustion efficiency of the metal component and combustion efficiency of the hydrocarbon component are higher for 50 percent superfine magnesium (average particle size, 24 microns) than the fine magnesium (average particle size, 66 microns).

(2) The addition of 0.8 percent gelling agent used to reduce the settling tendency of the 50-percent-superfine-magnesium slurry reduced the combustion efficiency of the hydrocarbon.

(3) The combustion efficiency of the magnesium component was unaffected by oxygen depletion as the fuel-air ratio was increased above stoichiometric up to the limits of the data at an equivalence ratio of 1.6. The rapid decline of the combustion efficiency of the hydrocarbon component in the rich region indicates that the magnesium burns first and the hydrocarbon reaction yields increasing amounts of incomplete combustion products as the fuel-air ratio is increased. This effect was not substantiated for the boron slurries (figs. 5(d) and 5(e)), where the oxygen deficiency in the rich region was reflected in combustion efficiencies that were reduced similarly for the boron and hydrocarbon.

(4) The crystalline boron had a higher combustion efficiency than the amorphous boron over the entire range of equivalence ratio tested.

(5) The combustion efficiency of the boron component in the crystalline-boron slurry had a higher combustion efficiency than the hydrocarbon, but the combustion efficiency of the boron component of the amorphous-boron slurry had a lower combustion efficiency than the hydrocarbon.

(6) At equivalence ratios richer than 0.8 the combustion efficiency of the JP-3 fuel alone decreased with increasing equivalence ratio. The combustion efficiency of the hydrogen is consistently higher than the carbon for this same range of equivalence ratios.

A comparison of the combustion efficiency of the JP-3 fuel in each of the fuels is shown in figure 6. When ϕ is greater than 1, the combustion efficiency values are limited by the oxygen deficiency. A curve of a reference efficiency for any fuel component is based on the assumptions that

- (1) All the oxygen is consumed
- (2) The composition of the combustion products (excluding nitrogen and unburned fuel) is the same as for complete combustion of a stoichiometric mixture.

The curve was computed from the relation

$$\eta_r = \frac{1}{\phi} \quad \text{when} \quad \phi > 1$$

and

$$\eta_r = 1.00 \quad \text{when} \quad \phi < 1$$

where η_r is the reference efficiency. A plot of these relations is shown in figure 6.

The ratio of the η_{HC} to η_r gives the curve $\frac{Q/f'}{h_{HC}/\phi}$ in figure 5(f). At equivalence ratios less than 0.8, the combustion efficiencies of JP-3 fuel was approximately the same for all the fuels investigated. At equivalence ratios higher than 0.8, the combustion efficiency of the JP-3 fuel was lower for the fuels containing magnesium.

Effective metal weight fraction. - The relative change in combustion efficiency of the metal and the hydrocarbon with equivalence ratio in effect changed the ratio of metal to slurry that was utilized in the combustion. The effective metal-to-fuel ratio is defined as

$$(W_M/W_F)_{\text{eff}} = \frac{\eta_M \times W_M/W_F}{\eta_M \times W_M/W_F + \eta_{HC} \times W_{HC}/W_F}$$

Figures 7(a) and 7(b) show that for the range of the experimental data the effective metal fraction of 50-percent-superfine magnesium and 30-percent crystalline-boron slurries was higher in the rich than in the lean regions. Since the effective metal fraction at rich mixtures is higher, the effective heating value per pound of air is correspondingly increased. The effective heating value would conceivably reach a maximum at an equivalence ratio where the metal consumes all the oxygen and the hydrocarbon does not burn at all.

Effective hydrogen-carbon ratio. - The relative change in the combustion efficiencies of the hydrogen and carbon when JP-3 fuel is burned alone changed the ratio of hydrogen to carbon that was utilized in the combustion.

The effective hydrogen-carbon ratio is defined as

$$(H/C)_{\text{eff}} = \frac{\eta_H}{\eta_C} (H/C)$$

Figure 8 shows that $(H/C)_{\text{eff}}$ increased with equivalence ratio for the range of the data. The same trend appears in the curve of $(H/C)_{\text{eff}}$ against ϕ that was computed from data given in reference 6. In this investigation aviation gasoline and diesel fuels were used to run several piston engines and the exhaust products were sampled and analyzed. The H/C ratios of JP-3 fuel and the fuels used in reference 6 are represented by the dashed lines.

Heat of combustion per pound of air. - The net effect of the different combustion efficiencies of the fuel components on the heat released by combustion per pound of air is shown in figure 9 as a function of equivalence ratio. The three magnesium slurries are compared in figure 9(a). The smaller particle size of the metal in the superfine-magnesium slurry gave a substantial increase in heat released per pound of air. The stabilizing additive reduced the heat released at richer than stoichiometric mixtures.

In figure 9(b) the superiority of the crystalline boron over amorphous boron in slurries is shown. The higher combustion efficiency of the crystalline boron can be attributed to its higher purity and smaller particle size.

The 50-percent-superfine-magnesium slurry, 30-percent-crystalline-boron slurry, and JP-3 fuel are compared in figure 9(c). Also shown are the heats released by combustion for each of the fuels for equivalence ratios up to 1.0 at 100-percent combustion efficiency.

The ideal maximum heating values per pound of air shown in the figure were found for each of the fuels by computing the equivalence ratio and corresponding ideal heating value per pound of air at which the component of highest heating value per pound of air is burned to completion and consumes all the oxygen. The remaining fuel components were assumed to behave as inert diluents and effect a temperature reduction by their heat capacity and phase changes.

The heat released by combustion per pound of air of all the fuels was increased over the values at an equivalence ratio of 1.0 by increasing the fuel-air ratio above stoichiometric. The experimental maximum

heating values for JP-3 fuel and 30-percent-crystalline-boron slurry occurred at equivalence ratios of 1.2 and 1.4, respectively. The experimental maximum value for the 50-percent-superfine-magnesium slurry was apparently beyond the range of the experimental data.

SUMMARY OF RESULTS

Several slurries were investigated to explore the characteristics of metal-hydrocarbon combustion, to determine the effect of fuel-air ratio on the combustion efficiency, and to determine how the metal and hydrocarbon separately contribute to the over-all combustion. The following results were obtained:

1. The combustion efficiency of magnesium powders in slurries was unaffected by oxygen depletion as fuel-air ratio was increased above stoichiometric to an equivalence ratio of 1.6, whereas the combustion efficiency of the hydrocarbon declined rapidly.
2. With the boron slurries the oxygen deficiency in the rich region was reflected in combustion efficiencies that were reduced similarly for the boron and hydrocarbon.
3. For the range of the experimental data the ratio of metal to slurry effectively utilized in the combustion of the slurries was higher at rich mixtures than at lean mixtures; the effective heating value per pound of air was correspondingly higher in the rich region.
4. The heat released by combustion per pound of air of all the fuels was increased over the experimental values at an equivalence ratio of 1.0 by increasing the fuel-air ratio above stoichiometric.
5. The slurry with the finer magnesium powder had a higher combustion efficiency than the slurry with the coarser powder.
6. The addition of gelling agent used to reduce the settling tendency of slurry fuels reduced the combustion efficiency of the hydrocarbon in the 50-percent-magnesium slurry.
7. The crystalline boron had a higher combustion efficiency than the amorphous boron.
8. The combustion products of the metal component of magnesium and boron slurries contained a negligible amount of nitrides.

CONCLUSIONS

1. Metal - hydrocarbon slurries of magnesium and boron can be burned with the metal burning about as efficiently as the hydrocarbon.
2. With hydrocarbon suspensions of metals as active as fine magnesium powder, the metal will burn preferentially to the hydrocarbon in oxygen deficient atmospheres.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 26, 1951

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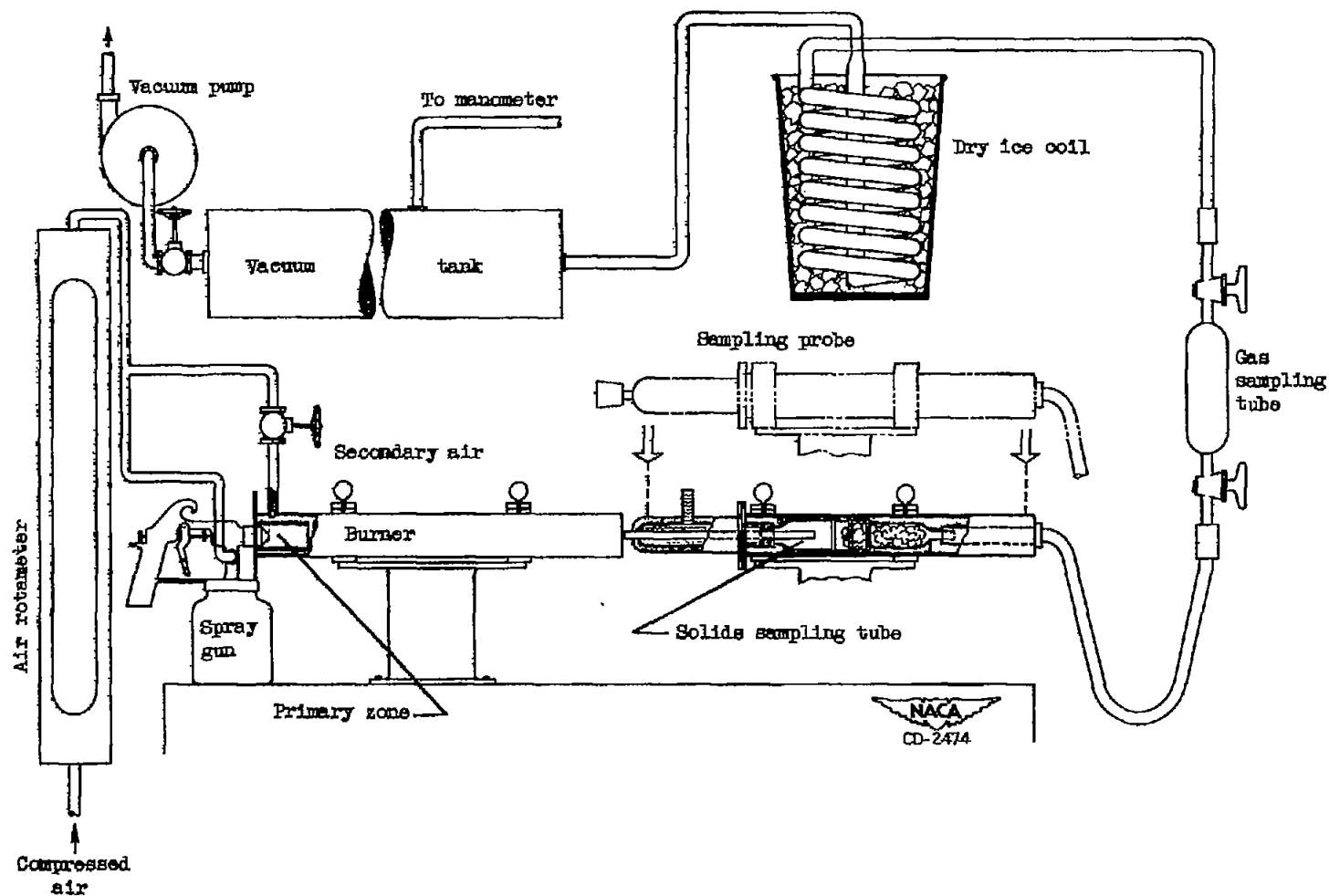


Figure 1. - Slurry burner and sampling apparatus.

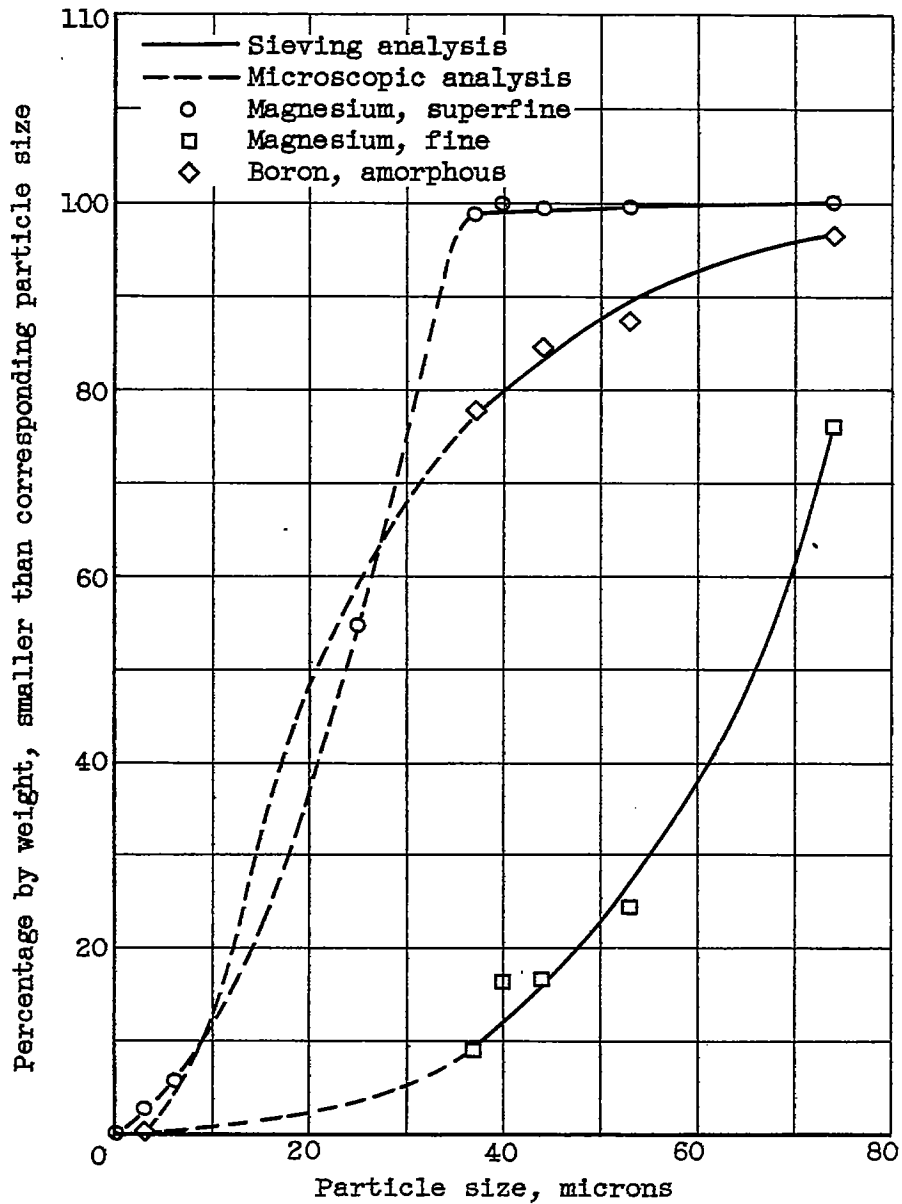
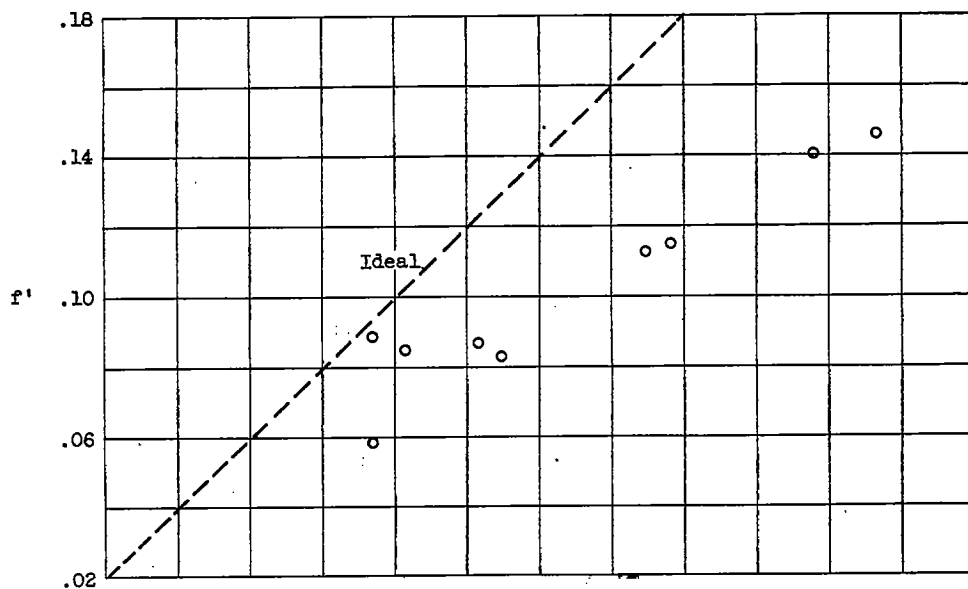
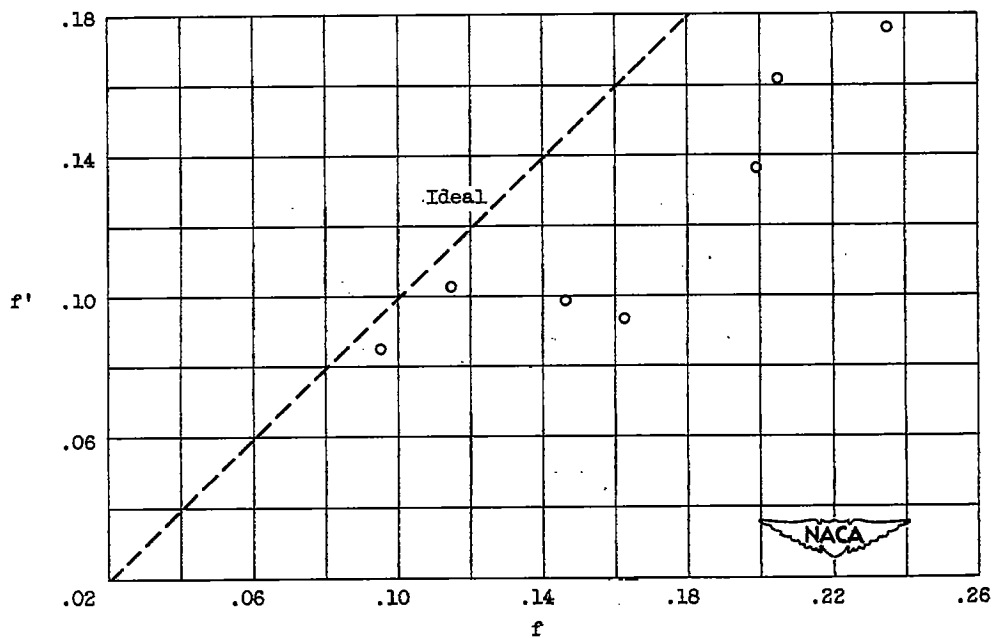


Figure 2. - Comparison of particle size distributions of metal powders from sieving and microscopic analysis.

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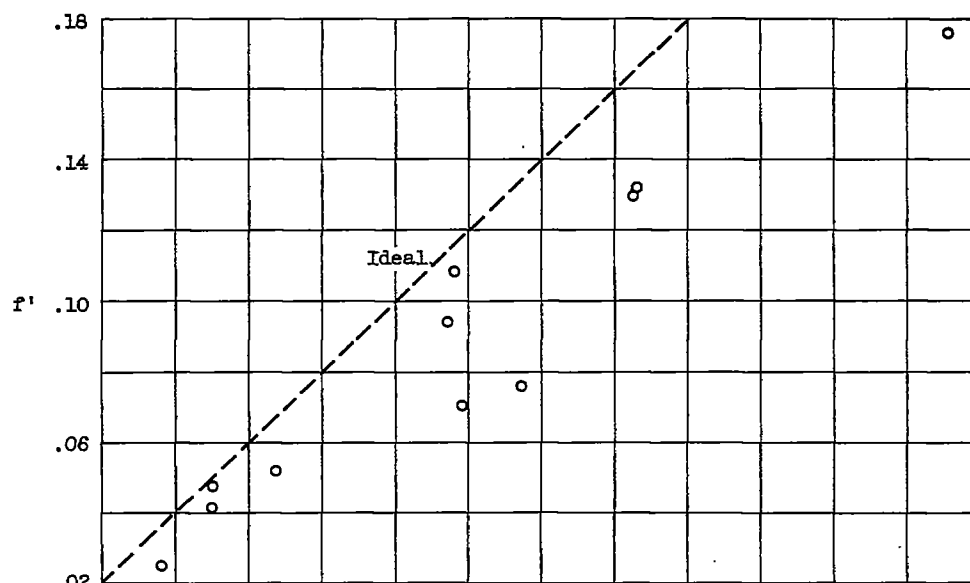
(a) Fuel, 50 percent fine magnesium in MIL-F-5624 grade JP-3.



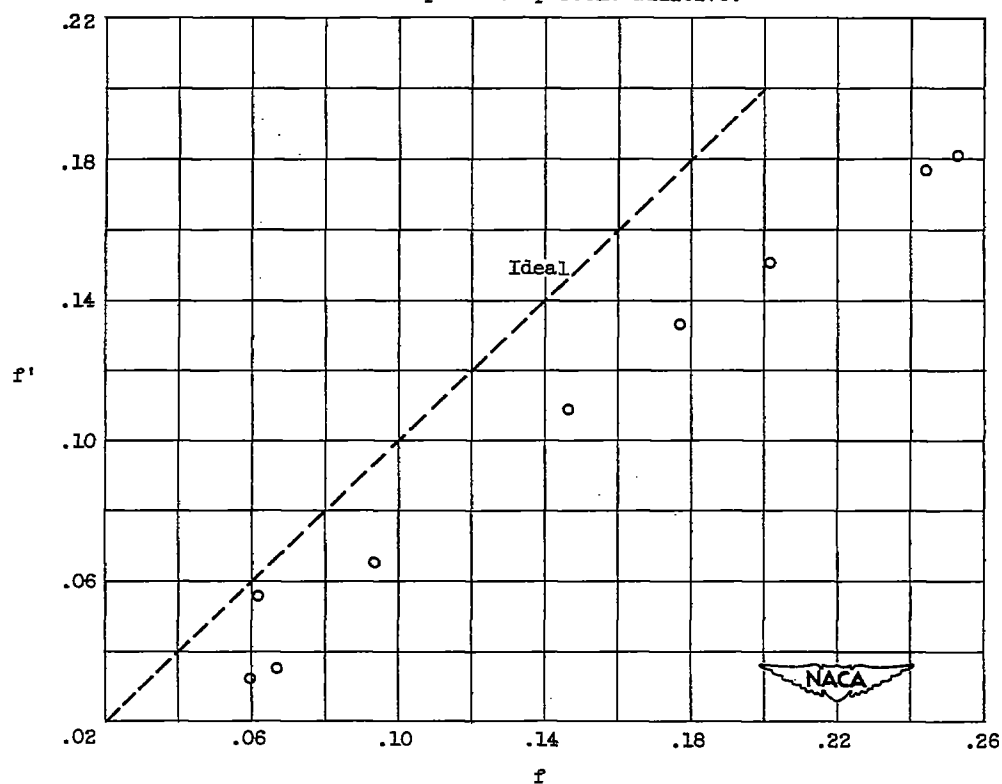
(b) Fuel, 50 percent superfine magnesium in MIL-F-5624 grade JP-3.

Figure 3. - Comparison of fuel-air ratio determined by inlet air and fuel flow (f) and fuel-air ratio determined by exhaust products analysis (f').

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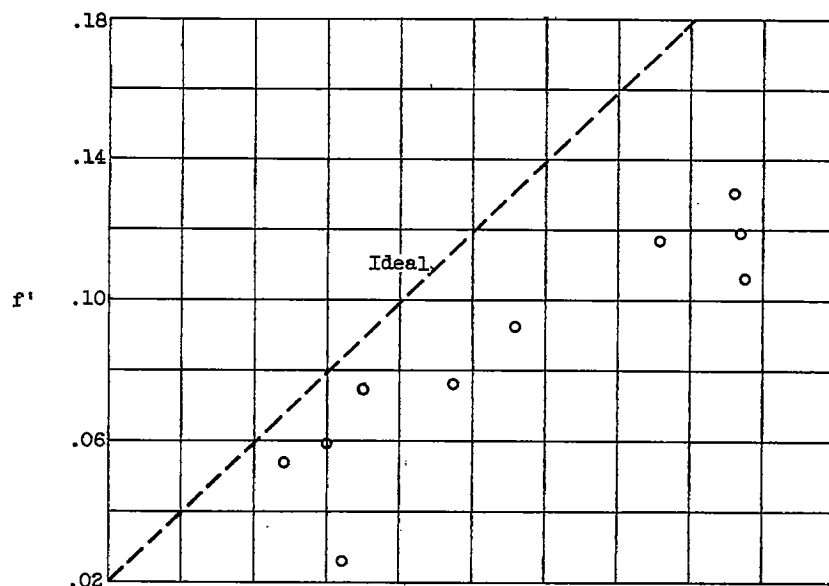


(c) Fuel, 50 percent superfine magnesium in MIL-F-5624 grade JP-3 plus 0.8 percent additive.

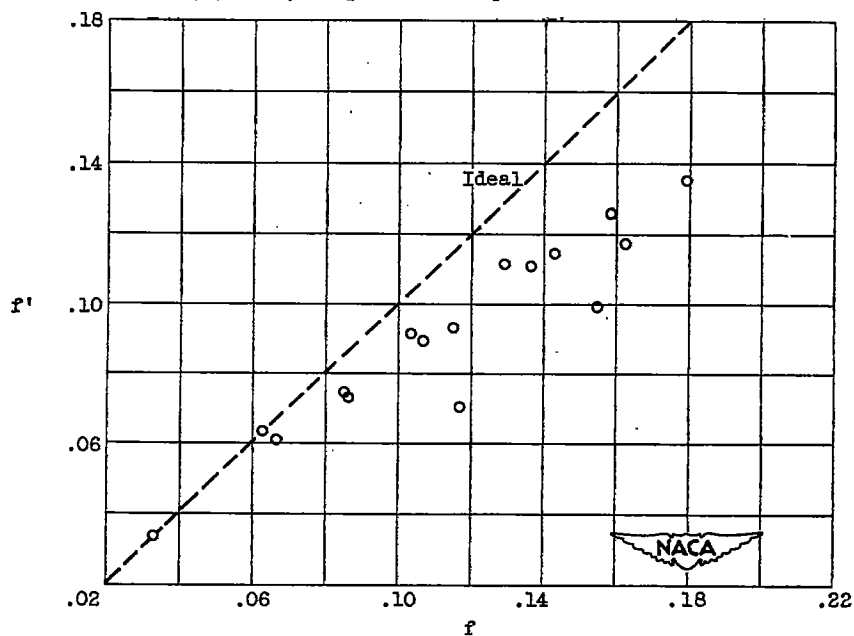


(d) Fuel, 30 percent crystalline boron in JP-3.

Figure 3. - Continued. Comparison of fuel-air ratio determined by inlet air and fuel flow (f) and fuel-air ratio determined by exhaust products analysis (f').

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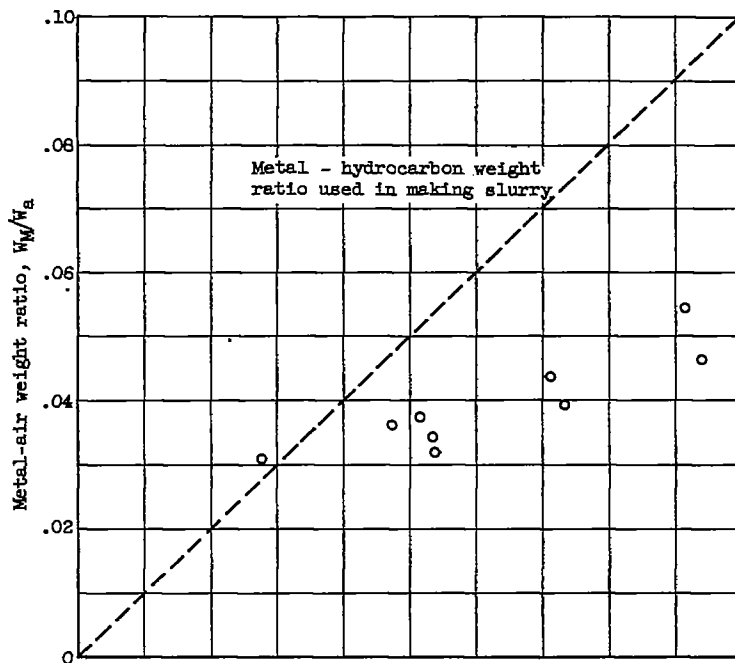
(e) Fuel, 30 percent amorphous boron in JP-3.



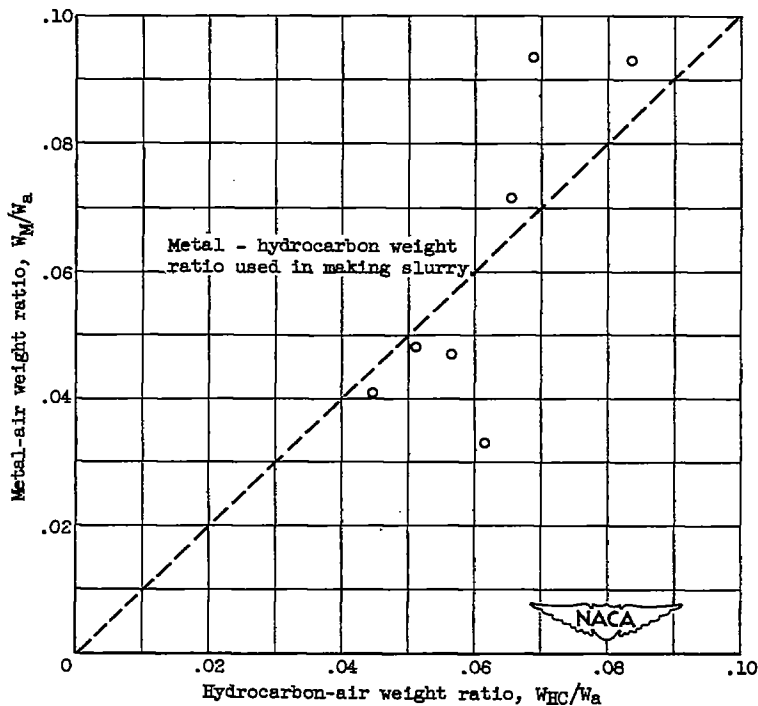
(f) Fuel, MIL-F-5624 grade JP-3.

Figure 3. - Concluded. Comparison of fuel-air ratio determined by inlet air and fuel flow (f) and fuel-air ratio determined by exhaust products analysis (f').

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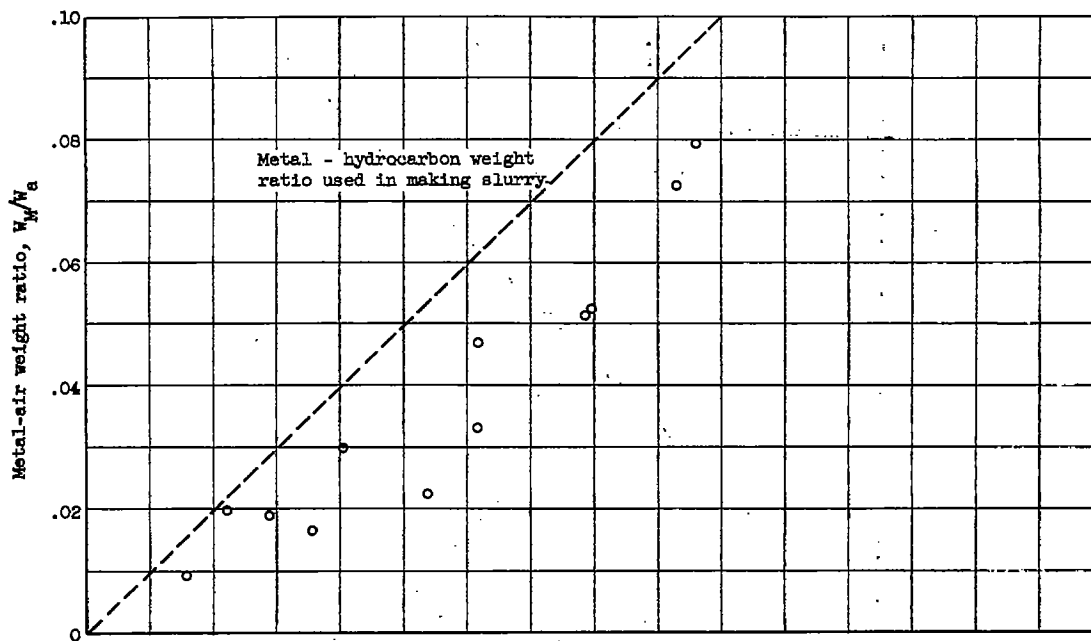
(a) Fuel, 50 percent fine magnesium in JP-3.



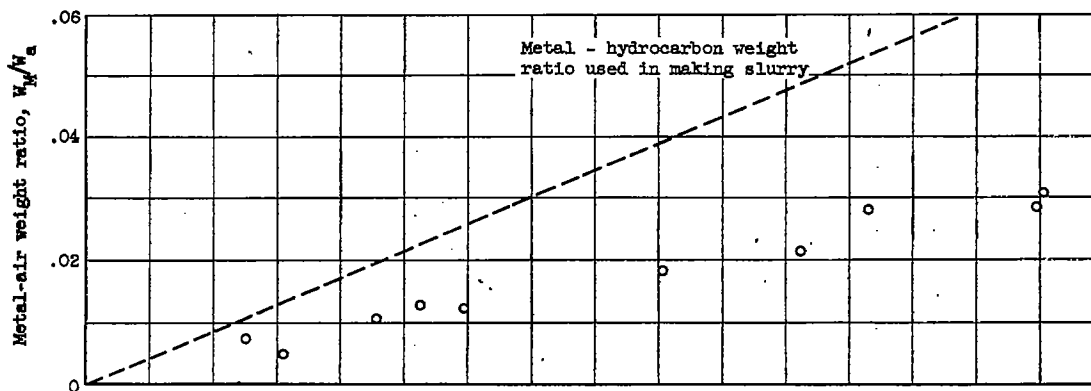
(b) Fuel, 50 percent superfine magnesium in JP-3.

Figure 4. - Metal - hydrocarbon ratio determined by combustion products analysis.

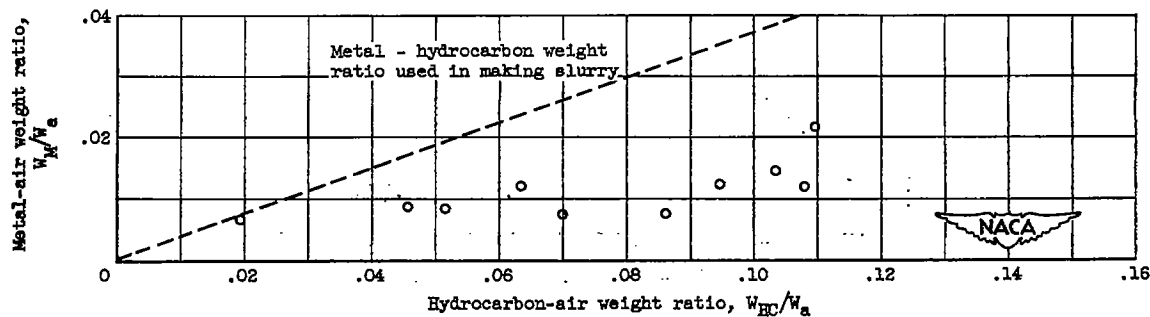
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(c) Fuel, 50 percent superfine magnesium in JP-3 plus 0.8 percent additive.



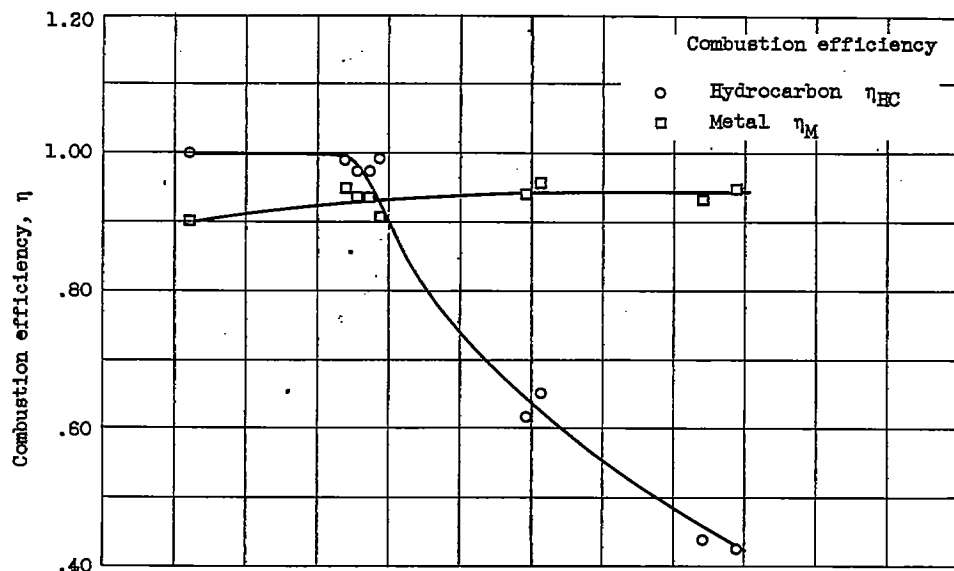
(d) Fuel, 30 percent crystalline boron in JP-3.



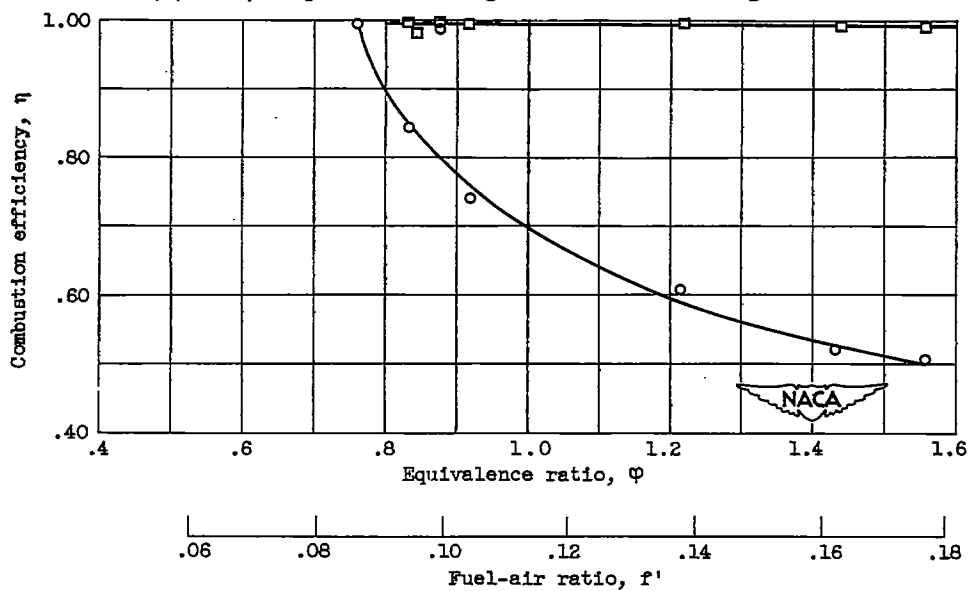
(e) Fuel, 30 percent amorphous boron in JP-3.

Figure 4. - Concluded. Metal - hydrocarbon ratio determined by combustion products analysis.

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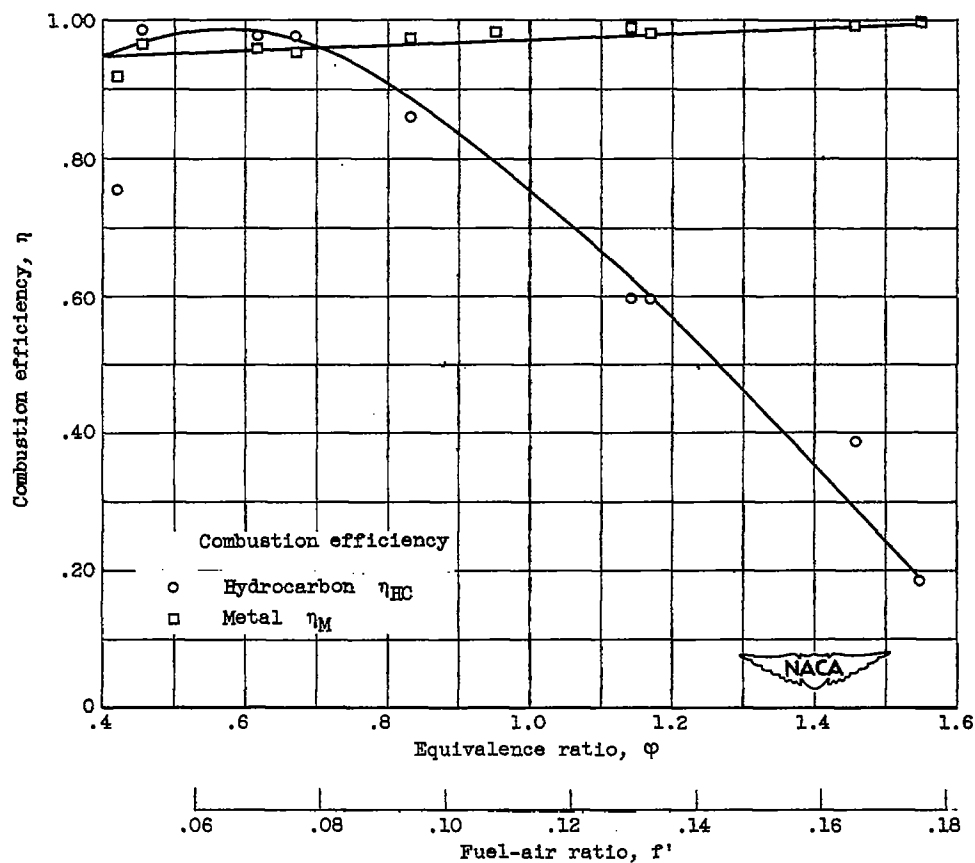


(a) Fuel, 50 percent fine magnesium in MIL-F-5624 grade JP-3.



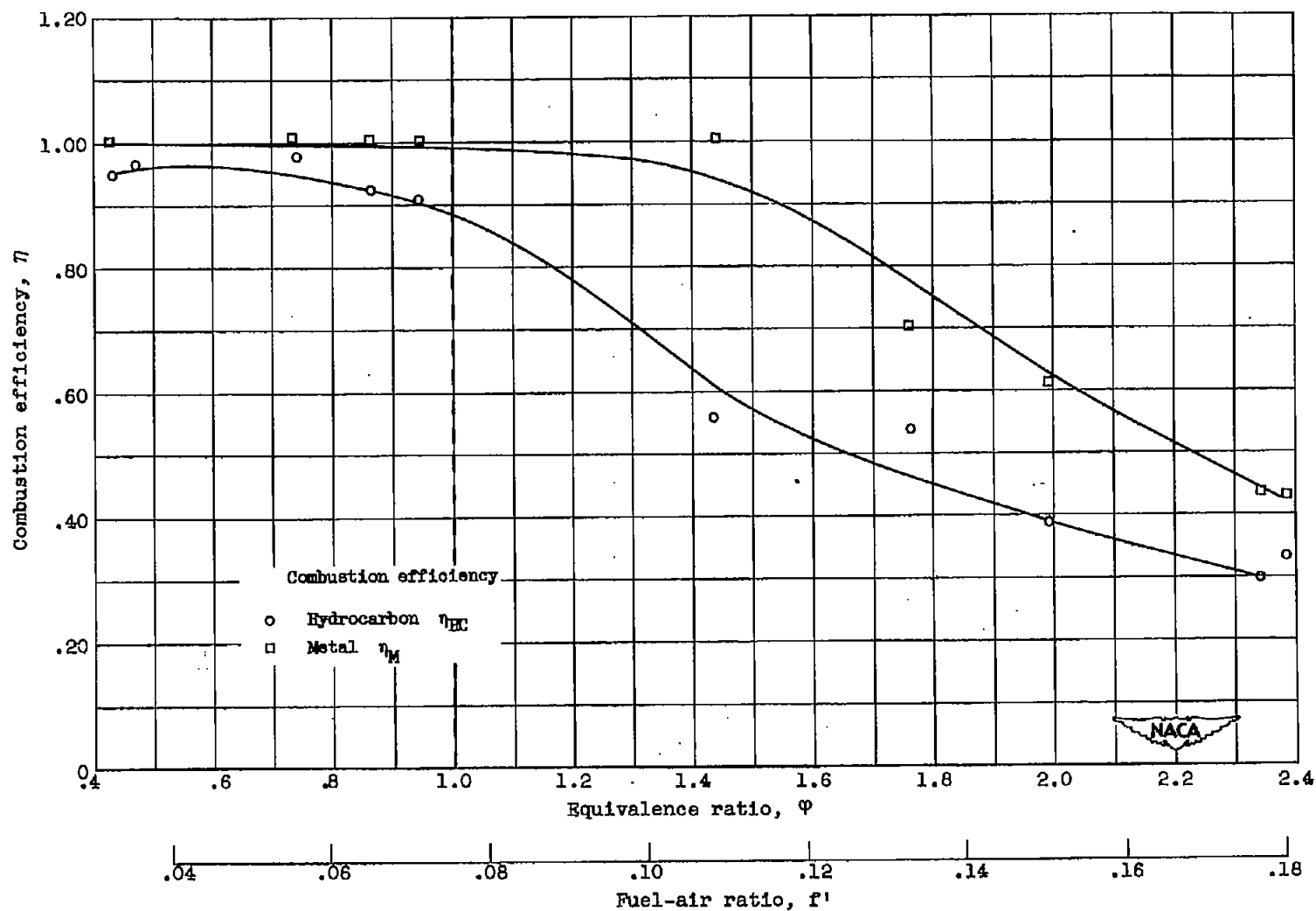
(b) Fuel, 50 percent superfine magnesium in MIL-F-5624 grade JP-3.

Figure 5. - Effect of equivalence ratio and fuel-air ratio on combustion efficiency of metal and hydrocarbon.



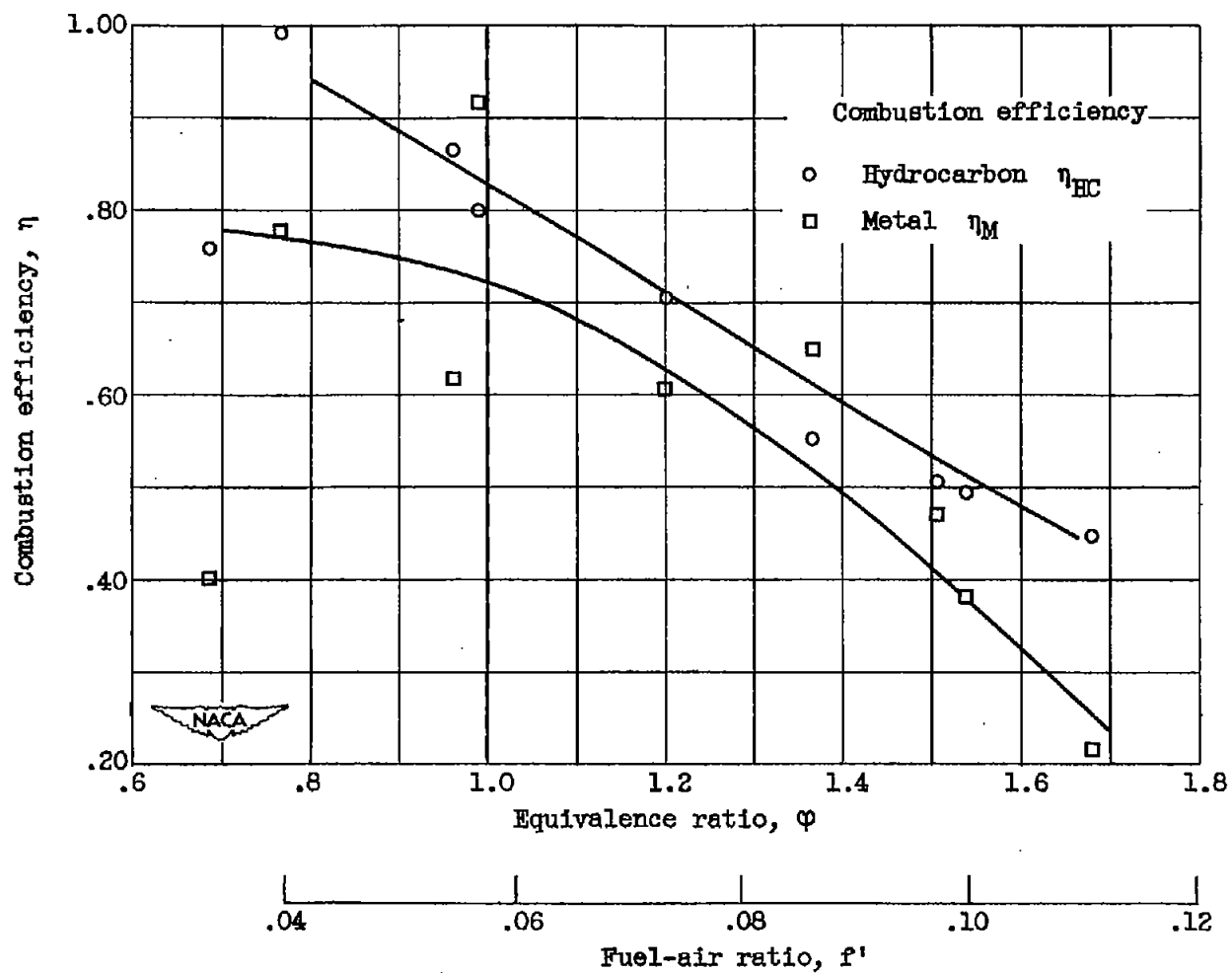
(c) Fuel, 50 percent superfine magnesium in MIL-F-5624 grade JP-3 plus 0.8 percent additive.

Figure 5. - Continued. Effect of equivalence ratio and fuel-air ratio on combustion efficiency of metal and hydrocarbon.



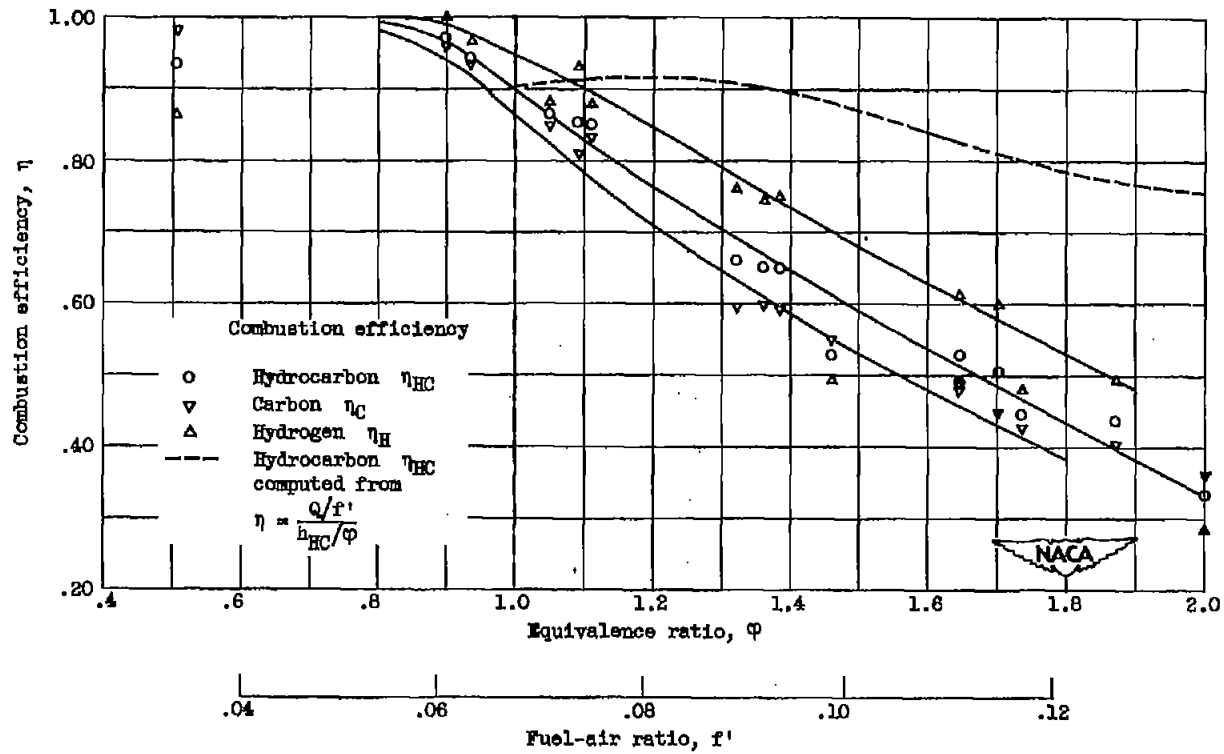
(d) Fuel, 30 percent crystalline boron in MIL-F-5624 grade JP-3.

Figure 5. - Continued. Effect of equivalence ratio and fuel-air ratio on combustion efficiency of metal and hydrocarbon.



(e) Fuel, 30 percent amorphous boron in MIL-F-5624 grade JP-3.

Figure 5. - Continued. Effect of equivalence ratio and fuel-air ratio on combustion efficiency of metal and hydrocarbon.



(f) Fuel, MIL-F-5624 grade JP-3. Q , heat released by combustion; h_{HC} , heat of combustion of hydrocarbon.

Figure 5. - Concluded. Effect of equivalence-ratio and fuel-air ratio on combustion efficiency of metal and hydrocarbon.

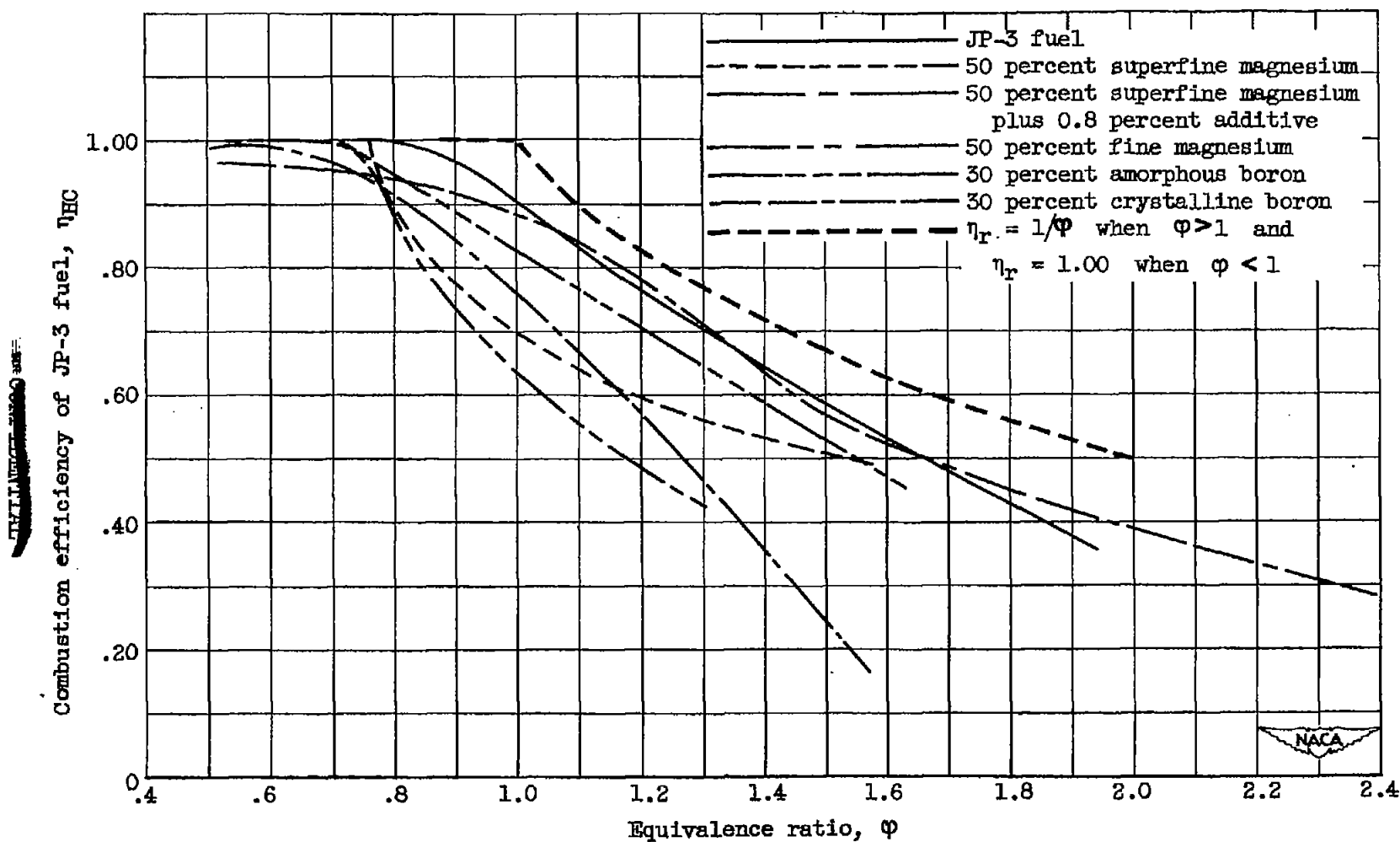
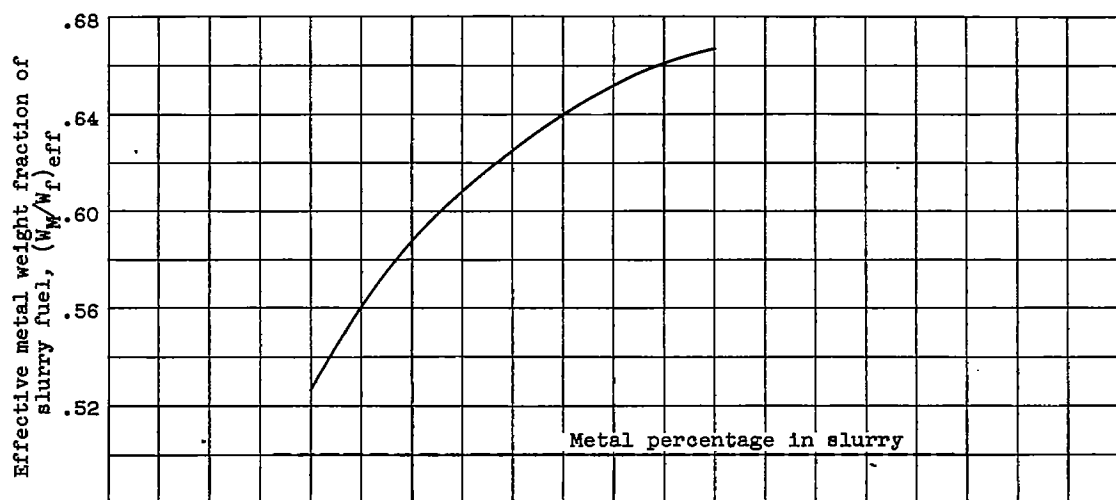
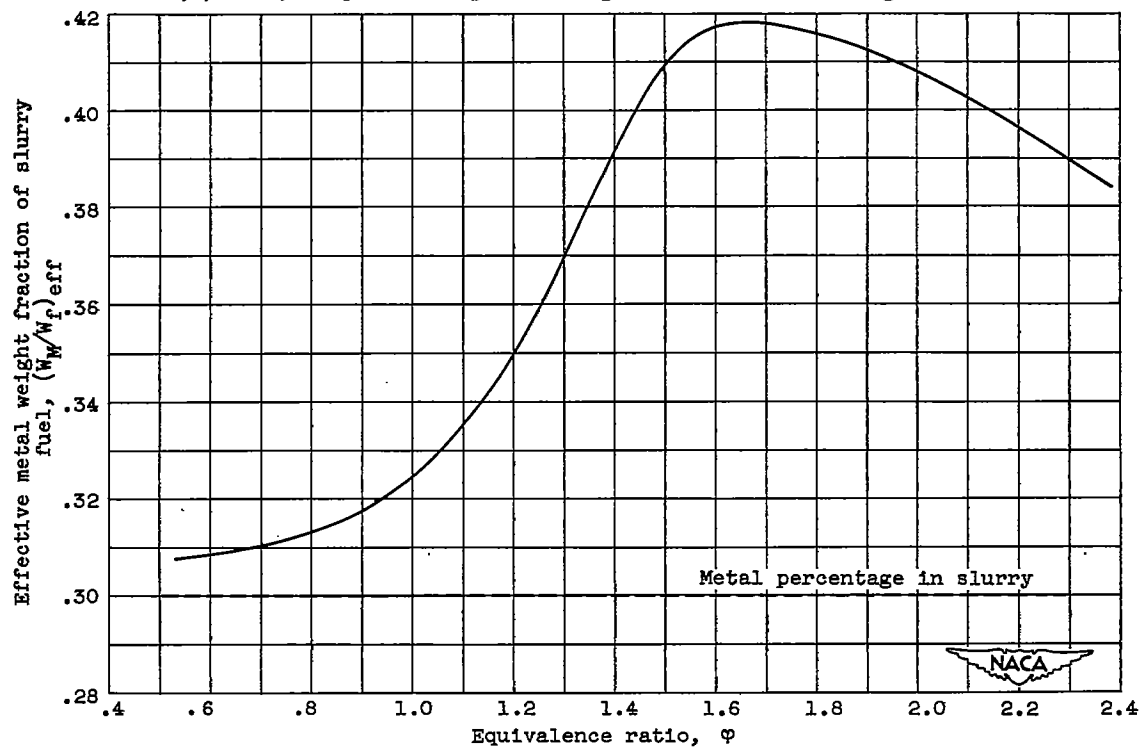


Figure 6. - Comparison of combustion efficiency of MIL-F-5624 grade JP-3 fuel in each fuel.
 η_r , reference efficiency.



(a) Fuel, 50 percent superfine magnesium in MIL-F-5624 grade JP-3.



(b) Fuel, 30 percent crystalline boron in MIL-F-5624 grade JP-3.

Figure 7. - Variation of effective metal percentage with equivalence ratio.

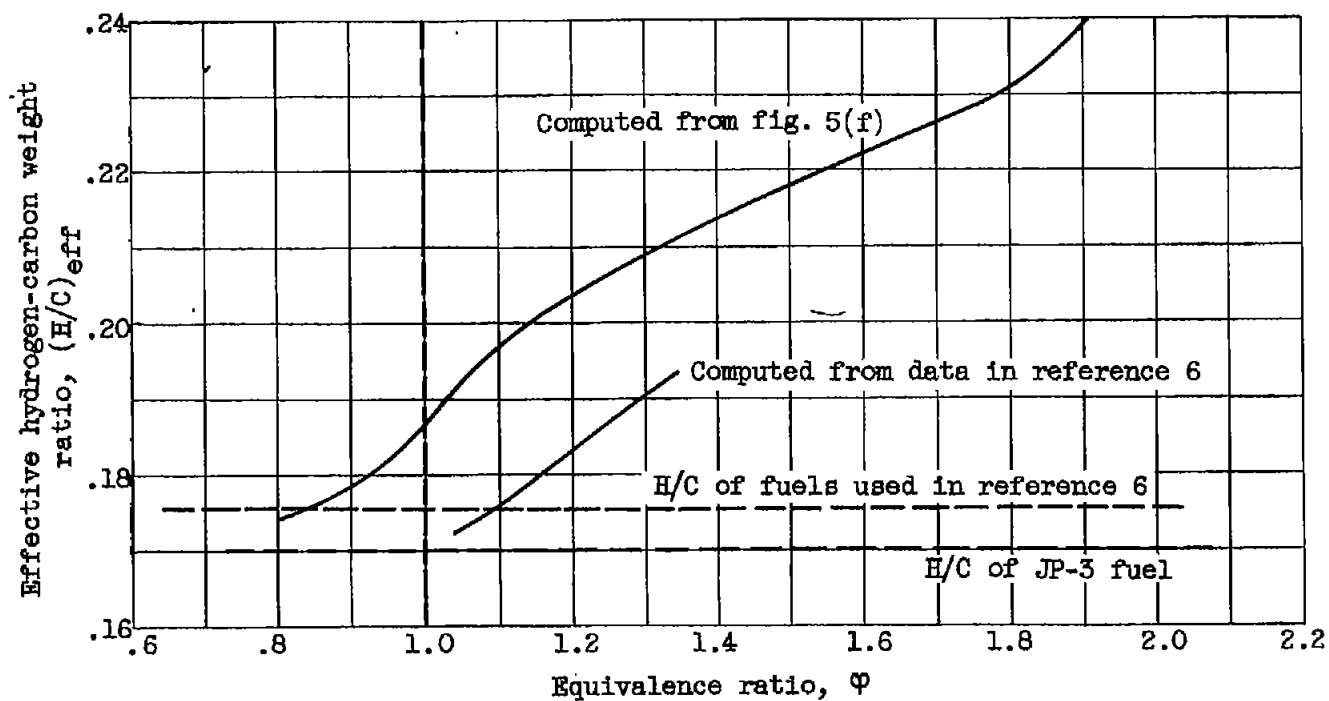
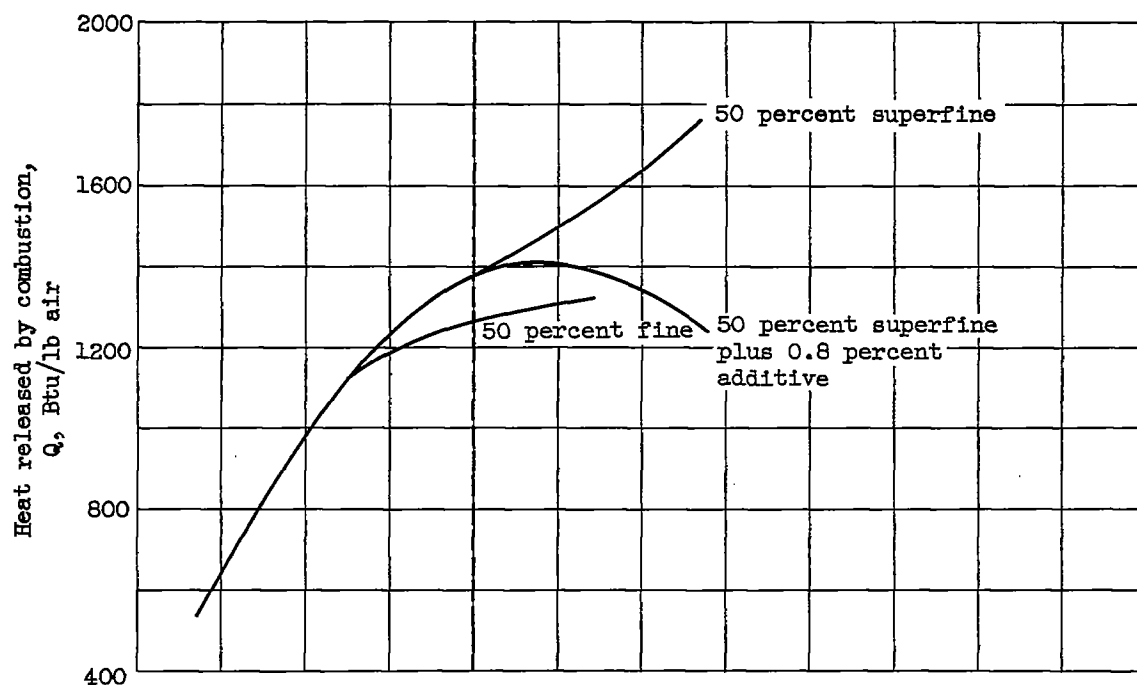
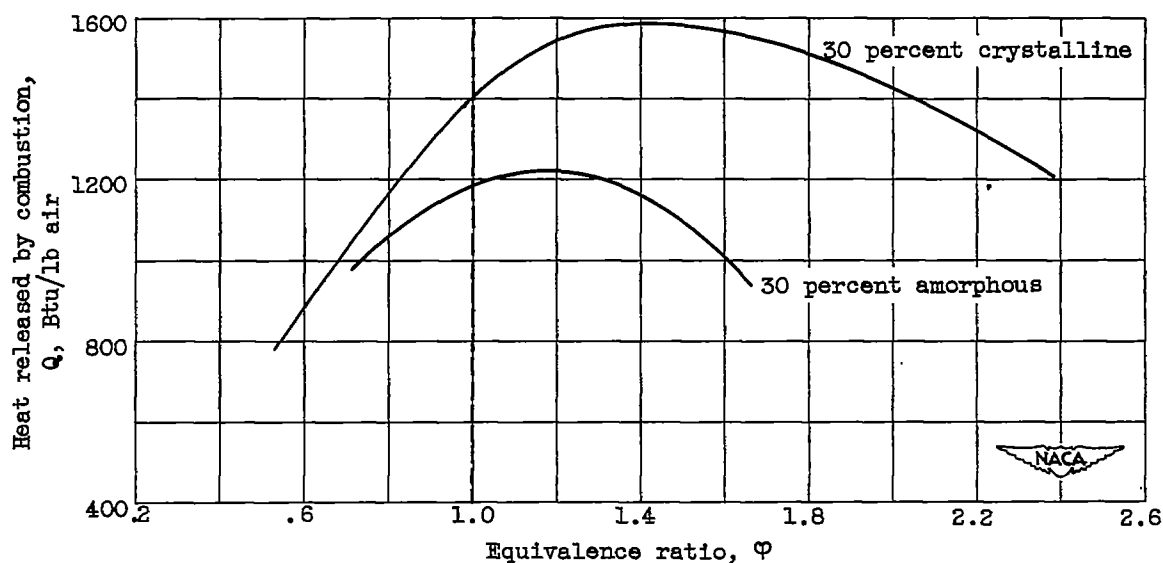


Figure 8. - Variation of effective hydrogen-carbon ratio with equivalence ratio.
Fuel, MIL-F-5624 grade JP-3.

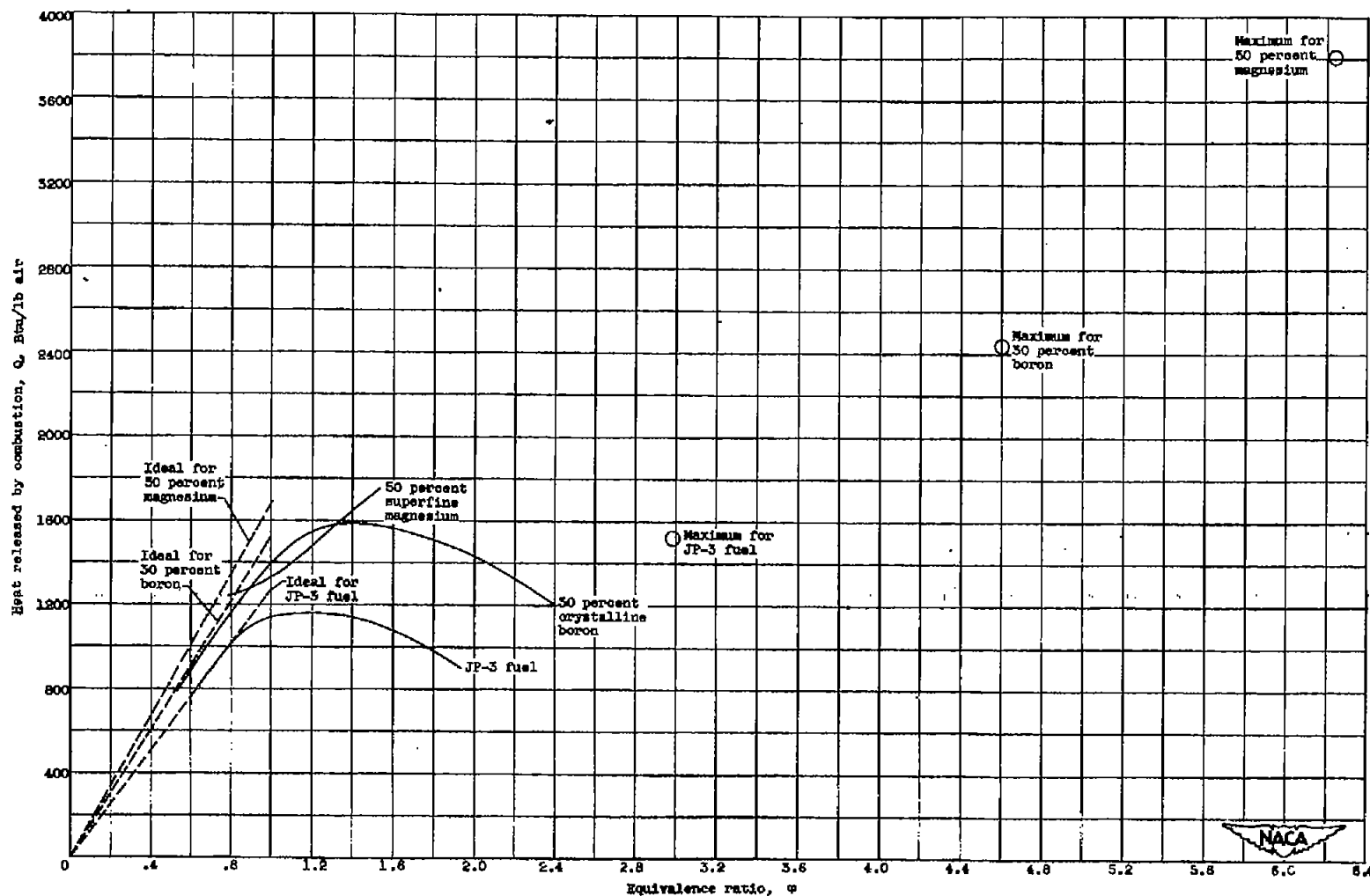


(a) Fuels, three magnesium slurries.



(b) Fuels, two boron slurries.

Figure 9. - Heat released by combustion per pound of air at varying equivalence ratio.



(c) Fuels: magnesium slurry, boron slurry, and MIL-P-5624 grade JP-5.

Figure 9. - Concluded. Heat released by combustion per pound of air at varying equivalence ratio.